Study on spectrum sharing method based on distance estimation for cognitive radio networks

Kenta Umebayashi
Tokyo University of Agriculture and Technology,
2-24-16, Nakacho, Koganei-shi, Tokyo, Japan 184-8588
Email: ume_k@cc.tuat.ac.jp

Janne J Lehtomäki
Centre for Wireless Communications,
University of Oulu
P. O. BOX 4500 FIN-90014 University of Oulu, Finland
Email: jannel@ee.oulu.fi

Yasuo Suzuki
Tokyo University of Agriculture and Technology,
2-24-16, Nakacho, Koganei-shi, Tokyo, Japan 184-8588
Email: ysuzuki-@cc.tuat.ac.jp

Abstract—We investigate a method to set the maximum allowable transmit power (MATP) for a secondary base station (SB) in dynamic spectrum sharing among secondary users (SUs) and primary users (PUs). In conventional methods, location information is assumed to be available. Thus, the MATP can be set by considering the shadowing between the SB and the PU receivers to satisfy a constraint. Specifically, probability that the interference caused by SB exceeds the allowable interference level should be less than the constrain target probability (CTP). We assume that the location information is not available at secondary network. Instead, the SB uses the received signal strength (RSS) from the PU transmitter for distance estimation. In this case, we have to consider shadowing not only between the SB and the PU receivers, but also between the PU transmitter and the secondary receiver(s). In addition, we also need to account for the uncertainty of the distance. Furthermore, we consider multipath fading. In order to satisfy the CTP, we proposed a two-step approach to setting the MATP where a transmission decision margin and a transmit power margin are utilized. To reduce these margins, we also proposed cooperative MATP setting method utilizing also RSS values from several SUs. Simulation results confirm the effectiveness of the proposed cooperative MATP setting method.

I. INTRODUCTION

To overcome the spectrum scarcity problem, one promising technique is spectrum sharing (SS), with cognitive radio techniques performed by secondary users (SUs) [1]. In the SS approach, SUs can use the spectrum even if the primary user (PU) is active with a constraint on interference at the PU.

In some research related to resource allocation with SS, it has been shown that transmit power control can improve the efficiency of spectrum utilization. However, in these studies, perfect instantaneous channel state information (CSI) or channel gain in the link from the SU transmitter to the PU receiver was assumed to be available [2]–[5]. However, this approach is not very practical.

Instead of the instantaneous CSI, several works assumed that location information (i.e., the distance between the SU transmitter and the PU receiver) is assumed to be available through a database and global positioning system [6]–[8]. Given the location information, the path loss (denoted by $L$) can be determined and the SU transmitter can set a maximum allowable transmit power (MATP) that gives sufficient PU protection using an appropriate margin as a countermeasure against uncertainty such as shadowing [6]–[8]. For setting margins appropriately, knowledge of statistics of uncertainties is required. In [9], transmit power control based on a soft decision was investigated. In this research, the statistics of the sensing metric were assumed to be known by the SUs. This fact is equivalent to the distance between the PU and the SU being available at the SU side.

On the other hand, in [10], $L$ is estimated based on measured information such as received signal strength (RSS) of PU signal and signal-to-noise power ratio (SNR). However, the effect of shadowing in the estimation was not considered sufficiently.

Motivated by the aforementioned research, in this paper we investigate a method to set the MATP for a secondary base station (SB) based on estimated distance between the SB and the PU transmitter. The SB will estimate the distance based on the RSS which is randomly fluctuating due to shadowing. Therefore, we have to consider not only shadowing in the link from the SB to the PU as in [6]–[8], but also shadowing in the link from the PU transmitter, or the PU base station (PB), to the secondary network (SN) consisting of the SB and SUs (terminals) to achieve an appropriate margin. In addition, there is a new issue caused by the unavailability of distance information. Specifically, appropriate margin for the shadowing effects can be obtained based on the knowledge of statistics of uncertainties, however the statistic depends on the actual distance even though the actual distance is unavailable. We will show that the proposed MATP setting can overcome the contradiction. A constraint for protecting PU is set for the constrain target probability (CTP) where a probability that the interference caused by SB exceeds the allowable interference level should be less than CTP.

For the issue of the unavailability of distance information, we propose a two-step approach to setting the MATP. In fact, the two steps consist not only of the transmit power setting but also of transmission decision and the both steps are performed based on distance estimation. In the transmit power setting and transmission decision, transmit power margin, $T_m$ and transmission decision margin, $d_m$, are used, respectively.

Furthermore, we investigate the effect of multipath fading which may affect not only the link from the SB to the PU.
but also the link from the PB to the SN. In fact, time domain averaging can suppress the effect of multipath fading in the link from the BP to SN [12], therefore the effect is not considered in this paper. On the other hand, the effect of the multipath fading in the link from the SB to the PU can not be suppressed, therefore we will investigate the effect of multipath fading in $T_m$ setting.

Numerical results will show that the SN throughput depends on the additional separation radius which is used for protection of PUs. In addition we will show an existence of optimal additional separation radius.

We propose the MATP setting method based on cooperative spectrum measurement to achieve smaller margins. The simulation results verify that the MATP setting method based on cooperative spectrum measurement improves the spectrum utilization compared to the MATP setting using spectrum measurement results only from the SB (MATP setting method based on individual spectrum measurement).

II. SYSTEM MODEL AND ASSUMPTIONS

The network model shown in Fig. 1 is discussed in Sect. II-A and the MATP setting assuming provided PU location information is explained in Sect. II-B.

A. Network model

As shown in Fig. 1, there are two networks: the PN and the SN. The PN consists of one central control station, such as a base station or broadcasting station, denoted by PB and with PUs corresponding to terminals. Suppose the PN and the SN are in the 2D plane $(d_x, d_y)$. Static environment is assumed thus, the locations of the PN and SN are fixed. The PN is licensed to operate over a frequency band with bandwidth $B$. The coverage of the PN is given by a circle with a radius $r_{c,p}$, with the PB located at the center. The PB and the SN locate at the origin $(0, 0)$ and $(d_{SU_0}, 0)$, respectively. A PU receiver located at the edge of the coverage area corresponds to the worst-case scenario [10], i.e., the PU receiver lies at $(r_{c,p}, 0)$. We define the extended PN coverage $d_g$ to consist of the actual coverage and an additional separation radius $\Delta d_g$ such that $d_g = r_{c,p} + \Delta d_g$. The main role of the additional

separation radius $\Delta d_g$ is to protect PUs [13], [14]. Thus, it is preferable that the SB may not operate in the area where $d_{SU_0} < d_g$. The SN consists of one base station, SB, and $N_s$ SUs (terminals). The radius of the SN coverage is denoted by $r_{c,s}$. The SUs are assumed to be uniformly distributed within a disk corresponding to the SN coverage area.

In a spectrum measurement, the RSS level $R_{PU_0 \rightarrow SU_n}$ from the PB transmission at the nth SU, $SU_n$, is given by:

$$R_{PU_0 \rightarrow SU_n} = T_{PU_0} - L(d_{SU_n}) + X_{PU_0 \rightarrow SU_n, \sigma_x}$$

$$= \bar{R}_{PU_0 \rightarrow SU_n} + X_{PU_0 \rightarrow SU_n, \sigma_x},$$

(1)

where $T_{PU_0}$ is the transmit power of the PB, $L(d_{SU_n})$ is path loss in dB, $d_{SU_n}$ is the distance between the PB and the SU, $X_{PU_0 \rightarrow SU_n, \sigma_x}$ reflects the attenuation due to shadowing, and $\bar{R}_{PU_0 \rightarrow SU_n}$ indicates the RSS without the shadowing effect. Note that the index $n = 0$ is used for base stations. We assume that antenna gains are 0 dBi. We employ the log-normal shadowing model [15] and assume that $X_{PU_0 \rightarrow SU_n, \sigma_x}$ are independent and identically distributed (i.i.d) normal random variables with zero mean and variance $\sigma_x^2$.

We assume a standard path loss model with a path loss exponent so that $L(d)$ for given distance $d$ is given by:

$$L(d) = 10 \log_{10} \left( \frac{4\pi d_0}{\lambda} \right)^2 + 10 \eta \log_{10} \left( \frac{d}{d_0} \right),$$

(2)

where $d_0$ denotes a reference distance and set to $d_0 = 1$ m, $\lambda$ is the wavelength of the carrier frequency, and $\eta$ denotes the path loss exponent. The coverage radii of the PN and the SN, $r_{c,p}$ and $r_{c,s}$, are set based on the minimum required received signal levels $\gamma_{PN}$ and $\gamma_{SN}$ at the PN and SN, respectively.

A interference level $I_{PU}$ at the PU receiver caused by the SB transmission is given by:

$$I_{PU} = T_{SU_0} - L(d_{PU_0-SU_0}) + X_{SU_0-PU, \sigma_x}$$

$$= \bar{I}_{PU} + X_{SU_0-PU, \sigma_x},$$

(3)

where $T_{SU_0}$ is the actual total transmit power of the SB, $d_{PU_0-SU_0}$ is the distance between the SU receiver and the SB, and $X_{SU_0-PU, \sigma_x}$ is the log-normal shadowing effect in the link. The constrain probability that the interference caused by the SB exceeds the allowable interference level is given by

$$P_C = P_r(I_{PU} > I_{th})$$

(4)

where $I_{PU}$ and $I_{th}$ indicate the interference level and the allowable interference level at the PU, respectively. We set a constraint $P_r(I_{PU} > I_{th}) \leq P_C$, where $P_C$ denotes the CTP. This constraint is used throughout this paper.

B. Maximum allowable transmit power setting with provided location information

To satisfy the CTP, the SB sets a proper $T_{SU_0}$. In the conventional MATP setting approach, it is assumed that location information $(d_{SU_0})$ is known [6], [7]. We denote this approach by MATP-P, where $P$ stands for "provided location information". In the MATP-P, $d_{PU_0-SU_0}$, is also available at
the SB since the SB knows $r_{e,p}$ [7]. Given this information, MATP satisfying the constraint can be set as: [7]

$$T_{\text{SU}_0,\text{max}}^{(Z)} = I_{\text{th}} + L(d_{\text{PU} \rightarrow \text{SU}_0}) - \sigma_x Q^{-1}(\hat{P}_C), \quad (5)$$

where the $P$ in $T_{\text{SU}_0,\text{max}}^{(Z)}$ indicates the MATP-P, $Q^{-1}(x)$ is the inverse Q-function and it is assumed that $\sigma_x$ is known at the SB. The term $\sigma_x Q^{-1}(\hat{P}_C)$ in (5) corresponds to a margin against the shadowing effect in the link from the SB to the PU.

III. PROPOSED MATP SETTING

To satisfy the CTP with unknown distance to the PB, we propose a two-step approach with distance estimation for setting the MATP. A flowchart of this procedure is shown in Fig. 2.

The actual problem caused by the unavailability of distance information is shown as follows. In general, the transmit power margin $T_m$ is set based on the worst case scenario, i.e., the SB locates at the edge of extended PN coverage, $d_{\text{SU}_0} = d_g$. In this case, the $T_m$ can satisfy the CTP only when the SB is in the region where $d_{\text{SU}_0} \geq d_g$. However, the SB may operate in the region where $d_{\text{SU}_0} < d_g$ since estimated distance is used. In this case, the CTP can not be satisfied. For overcoming this problem, the transmission decision with the decision margin is used to protect the PUs.

The procedure of the setting the MATP is as follows. The SN first calculates an estimate of the distance. The distance estimation is based on either the RSS value $R_{\text{SU}_0 \rightarrow \text{SU}_0}$ collected by the SB alone (referred to as MATP-I, where $I$ stands for “individual measurement”) or the RSS values $R_{\text{PU}_0 \rightarrow \text{SU}_0}$ and $R_{\text{SU}_0 \rightarrow \text{SU}_n}$ collected by the SB and $N_S$ SUs ($n = 1, 2, \cdots, N_S$) (referred to as MATP-C, where C stands for “cooperative measurement”).

The SB first decides if transmission is allowed by estimating whether the SB resides within extended PN coverage, $d_g$. The

SB arrives at a decision by comparing the estimated distance to the distance $d_g + d_m$, where $d_m$ is a transmission decision margin that is used to guarantee the protection of the PUs when the SB actually resides in the extended PN coverage, i.e., $d_{\text{SU}_0} \leq d_g$. The protection is guaranteed by setting the $d_m$ in such a way that the transmission within the extended PN coverage is allowed with a probability equal or less than the CTP, $\hat{P}_C$. The result of this is a binary transmission decision variable, $D_T$, where $D_T = 1$ indicates that the transmission is allowed, and $D_T = 0$ rejects it. If transmission is allowed, the SB continues to the next step.

In the second step, the SB applies a transmit power margin $T_m$ that guarantees the PU protection when the SB resides outside the extended PN coverage, i.e., $d_{\text{SU}_0} > d_g$. The transmit power margin $T_m$ depends on the locations of the PU receiver and the SB corresponding to the transmitter. Since the exact location information is not available at the SB, we set $T_m$ considering the worst case in which the PU receiver lies in the neighborhood of edge of the extended PN coverage and the SB is at a location leading to maximum $T_m$. This fact will be confirmed in Fig. 3.

A. Distance estimation in MATP-I and MATP-C

From (1) and (2), $d_{\text{SU}_0}$ can be estimated with:

$$d_{\text{SU}_0}^{(Z)} = d_0 10^{-\frac{(R^{(Z)} - \text{TPU}_0 - 20 \log_{10}(4\pi d_0/\lambda))/\text{cent}(10n)}{}}. \quad (6)$$

where the superscript $(Z)$ indicates type of MATP, i.e., $(C)$ for MATP-C and $(I)$ for MATP-I, and $R^{(Z)}$ for MATP-I and MATP-C are

$$\hat{R}^{(I)} = R_{\text{PU}_0 \rightarrow \text{SU}_0}, \quad (7)$$

$$\hat{R}^{(C)} = \frac{\sum_{n=0}^{N_S} R_{\text{PU}_0 \rightarrow \text{SU}_n}}{1 + N_s}, \quad (8)$$

respectively. In the case of MATP-C in (8), RSS values from different SUs are averaged in order to suppress the effect of shadowing.

B. Transmission decision with transmission decision margin

The transmission decision rule is defined as:

$$D_T = \begin{cases} 
1: & (d_{\text{SU}_0}^{(Z)} \geq d_g + d_m^{(Z)}) \\
0: & (d_{\text{SU}_0}^{(Z)} < d_g + d_m^{(Z)}). 
\end{cases} \quad (9)$$

The transmission decision margin $d_m^{(Z)}$ is set to satisfy the equality:

$$\Pr(d_{\text{SU}_0}^{(Z)} \geq d_g + d_m^{(Z)} | d_{\text{SU}_0} = d_g) = \hat{P}_C. \quad (10)$$

This shows that the probability of allowing transmission when the SB is within the extended PN coverage is always less than or equal to the CTP, i.e., $\Pr(D_T = 1 | d_{\text{SU}_0} = d_g) \leq \hat{P}_C$. 

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Fig. 2. A flowchart of the proposed MATP setting procedure.
C. Maximum allowable transmit power setting based on distance estimation

In the MATP-I and the MATP-C, we use a transmit power margin $T_m^{(Z)}$ to satisfy the constraint in the region where $d_{SU_0} > d_g$. According to the transmission decision, the MATP is given by:

$$T_m^{(Z)}_{SU_0, \text{max}} = \begin{cases} I_{th} + L(d_{SU_0}^{(Z)} - r_{c,p}) - \sigma_x Q^{-1}(P_C) - T_m^{(Z)}_m; \quad (D_T = 1) \quad (11) \\ \text{No transmission;} \quad (D_T = 0). \end{cases}$$

Now we define the constraint probability as a function of the margin $T_m^{(Z)}$ for a given $d_{SU_0}$ as $P_C(T_m^{(Z)} | d_{SU_0})$ where the required margin depends on the distance $d_{SU_0}$. Thus, we consider the worst case $d_{SU_0}$ when setting the margin. This can be expressed as:

$$T_m^{(Z)} = \max_{d_g < d_{SU_0} < \infty} P_C^{-1}(P_C | d_{SU_0}). \quad (12)$$

To see the worst case for $T_m^{(Z)}$, (i.e., $T_m^{(Z)*}$), $T_m^{(Z)}$ satisfying $P_C$ as a function of $d_{SU_0}$ in the cases of the MATP-I and the MATP-C is shown in Fig. 3. The parameters are set as $N_S = 4$, $\eta = 3$, $\sigma_x = 9$ dB, $r_{c,p} = 3.68$ km, $r_{c,s} = 500$ m. Values for $d_g$ of 3.7 km and 4.2 km are used.

In the region where $d_{SU_0} < d_g$, the margin $d_m$ is used in the transmission decision variable $D_T$, to satisfy the constraint. That is, $Pr(D_T = 1) \leq P_C$, therefore $T_m^{(Z)} = 0$. The maximal values are in the region where $d_{SU_0} \geq d_g$ and close to $d_{SU_0} = d_g$. In this region, $T_m^{(Z)}$ increases at a rapid rate. This is because $Pr(D_T = 1)$ increases, and to satisfy the constraint, a larger $T_m^{(Z)}$ is required. In the region to the right of the maximum, $T_m^{(Z)}$ decreases slowly since $Pr(D_T = 1) \gg P_C$ and the far SB transmitter requires smaller transmit power margin. Since the SB does not have exact information about its location $d_{SU_0}$, we set the transmit power margin to the maximal value, $T_m^{(Z)*}$.

In the case when $d_g = 3.7$ km, the SB may be located near the PU receiver, and thus it requires a significantly large margin. For example, in the case of the MATP-I, $T_m^{(Z)*} = 34$ dBm. On the other hand, in the case of the MATP-C with $d_g = 4.2$ km, the required margin is only $T_m^{(Z)*} = 5$ dBm. The difference between these margins is 29 dBm, and is caused by not only the gain of the cooperative measurement but also by the appropriate $d_g$ setting.

In Fig. 4, $T_m^{(Z)*}$ as a function of $d_g$ in terms of the MATP-C and the MATP-I is shown. The parameters are set as $N_S = 4$, $\eta = 3$, $\sigma_x = 9$ dB, $r_{c,p} = 3.68$ km, $r_{c,s} = 500$ m. In addition, we derive not only $T_m^{(Z)*}$ considering the shadowing but also $T_m^{(Z)*}$ considering both shadowing and multipath fading. In this paper, block Rayleigh fading model is assumed, thus during one continues transmission the effect of the multipath fading is constant.

This result shows that smaller values $d_g$ require significantly large margins. In the case of the MATP-I, the difference between $d_g = 3.7$ km and $T_m^{(Z)*}$ at $d_g = 4.2$ km is 17 dBm and in the case of the MATP-C the difference is still 15 dBm.

It is interesting to note that the multipath fading effect reduces $T_m^{(Z)*}$ compared to the case only considering shadowing effect. Typically, the margin is set based on the worst case, thus $T_m^{(Z)*}$ based on only shadowing effect is used in numerical evaluation.

IV. NUMERICAL RESULTS

In this section, MATP-P, MATP-I, and MATP-C are compared in terms of the average capacity, $C_{\text{down}}$ similarly as in [7], [8]. In fact, the MATP-P is equivalent to the approach.
proposed in [7], [8] where perfect location information is assumed to be available. A derivation of the average capacity is shown in the following subsection.

The CTP is set to $P_C = 0.01$. The assumed center frequency of the spectrum band is 600 MHz, which is used in digital TV broadcasting but the application of the proposed method is not limited to it. We set the path loss exponent as $\eta = 3$. The transmit power of the PB is set to $T_{P_{U_0}} = 60$ dBm and the total transmit power of the SB is always limited to the maximum value of $T_{total} = 30$ dBm. The minimum required received signal levels, $\gamma_{SN}$ and $\gamma_{PN}$, are set as $-75$ dBm and $-85$ dB, respectively leading to the radii $r_{c,p} = 3.68$ km and $r_{c,s} = 0.5$ km.

A. Average capacity obtained by Power and channel allocation

The SB allocates a transmit power $T_{n,l,mW}$ for the $n$th SU transmission on the $l$th sub-channel, where the bandwidth $B$ is divided into $L$ sub-channels. The aim of this resource allocation is to maximize the down-link capacity $C_{down}$ while keeping the interference constraint and a total transmit power constraint. This is expressed as

$$\max C_{down} = \max \left\{ \frac{1}{N_L} \sum_{l=1}^{L} \sum_{n=1}^{N_S} a_{n,l} \log_2 \left( 1 + \frac{|h_{n,l,SB}|^2 T_{n,l,mW}}{N_{mW} + |h_{n,l,SB}|^2 T_{U_0,mW}/L} \right) \right\}, \quad (13)$$

subject to

$$\sum_{n=1}^{N_S} a_{n,l} \leq 1, \forall l, a_{n,l} \in \{0, 1\} \forall n, l, \quad (14)$$
$$\sum_{n=1}^{N_S} \sum_{l=1}^{L} a_{i,l} T_{n,l,mW} \leq T_{total,mW}, \quad (15)$$
$$\sum_{n=1}^{N_S} \sum_{l=1}^{L} a_{i,l} T_{n,l,mW} \leq T_{SB_{max,mW}}, \quad (16)$$

where $a_{n,l}$ is a sub-channel allocation indicator (i.e., $a_{n,l} = 1$ indicates that the $l$th sub-channel is allocated to the $n$th SU transmission; otherwise $a_{n,l} = 0$), $h_{n,l,SB}$ denotes the channel gain between the PB and the $n$th SU for $l$th sub-channel, and $N_{mW}$ is the noise power in one sub-channel. The constraints are as follows: (14) indicates that each sub-channel is assigned to only one SU, (15) is the total transmit power constraint due to SB limitations or constraints by a regulator, and (16) is the interference constraint. The variance of channel gain $h_{n,l,PB}$ is determined by the distance between the PB and the $n$th SU and the log normal shadowing. Without loss of generality, we use capacity normalized by sub-channel bandwidth and $L$ in (13). The solution of this optimization problem can be found by a simple water-filling scheme as described in [7].

\[\text{In this paper, we use two units, "mW" and "dBm" for variables corresponding to power values. When unit in a variable is mW, "mW" is noted in the suffix (for example } T_{n,l,mW}, \text{ but when the unit is dBm, notation of unit is abbreviated (for example } T_{n,l}).\]
Fig. 6. $\hat{C}_{\text{down}}^*$ as a function of extended PN coverage $d_g$ for MATP-C ($N_s = 4$) and MATP-I, with $P_C = 0.01$, $d_g = 9$ dB, $r_{c,p} = 3.68$ km, $r_{c,s} = 500$ m, and $d_{\text{max}} = 40$ km.

$r_{c,p} \leq d_{SU_0} \leq d_{\text{max}}$. In the evaluation performed here, we use $d_{\text{max}} = 40$ km. This metric $\hat{C}_{\text{down}}^*$ indicates the average of $\hat{C}_{\text{down}}(d_{SU_0})$ in the $d_{SU_0}$ domain.

Fig. 6 shows $\hat{C}_{\text{down}}^*$ as a function of $d_g$ for the MATP-C and the MATP-I. In both cases, the optimum point where $\hat{C}_{\text{down}}^*$ is maximized is around $d_g = 4.2$ km.

V. CONCLUSION

In this paper, we investigated methods to set the MATP for SS. In our proposed approach, the SB sets the MATP based on an estimate of the distance between the SB and PB (transmitter). We compared against the MATP-P where location information is available at the SB.

To satisfy the CTP, the SB has to consider three issues: shadowing from the PB (transmitter) to the SU, shadowing from the SB to the PU receiver, and the lack of location information. To handle these issues, we proposed a two-step approach to set the MATP where two margins, the transmission decision margin and the transmit power margin, were employed. The former is to guarantee the protection of the PUs when the SB resides within the extended PU network (PN) coverage, and the latter is to guarantee the PU protection when the SB resides outside of the extended PN coverage.

We also investigate the effect of multipath fading especially in the link from the SB (transmitter) to the PU receiver. The results show that in fact multipath fading reduces the required transmit power margin.

Numerical results verified our approach and showed that the MATP-I and the MATP-C can satisfy the constraint for any placement of the SN. Furthermore, in the MATP-C, cooperative measurements are used and the numerical results demonstrated that the MATP-C always outperforms the MATP-I in terms of average SN capacity. Setting the extended PN coverage range is also important since it significantly affects the average capacity, as was shown by the numerical results. In addition, we demonstrated that there is also an optimum range for the extended PN coverage that can maximize average capacity performance.

REFERENCES